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AN INVESTIGATION OF PRELOAD RELAXATION
BEHAVIOUR OF THREE ZINC-ALUMINIUM ALLOYS

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Abstract

Preload relaxation tests have been carried out on three sand-cast Zinc-Aluminium alloys, No3, No5 and No2. The equipment used for load relaxation tests consists of a load-monitoring device, an oil-bath and a data-acquisition system. A load cell monitoring device was used to monitor the load loss in an ISO-metric M6 x 1 steel screw set into sand castings of alloys No3, No5 and No2 and tightened to produce an initial preload of 6 kN. The castings were held at constant temperature in the range 80-120°C in an oil-bath. The oil-bath maintains the desired test temperature throughout the experiment. All tests were conducted in duplicate for periods of up to 160 hours. A parametric equation of the form: $\ln L = \alpha [Q/RT - \ln B - \ln t]$, was used for a quantitative analysis of the preload relaxation behaviour of alloys under different testing conditions, where L is the load after time t, Q an activation energy for load relaxation, R the universal gas constant and a and B are constants. For all alloys, the initial load loss was high, decreasing gradually with time but not ceasing. The results showed that the load loss increased rapidly with temperature and almost all of the relaxation curves approximated to a logarithmic decay of load with time. Alloy No2 had the best resistance to load loss, with No5 next and No3 worst at all temperatures. The lower resistance to relaxation of alloy No3 was mainly due to the lower relaxation strength of copper-free primary dendrites whereas in alloys No2 and No5, the higher copper contents contribute greatly to their relaxation strength in the form of second-phase particles.

Riassunto

Sono stati eseguiti test di rilassamento su tre leghe di alluminio-zinco, colate in sabbia, indicate come No3, No5 ed No2. Per i test è stato usato un sistema costituito da una cella di carico, un bagno ad olio ed un sistema di acquisizione dati. La cella di carico è stata impiegata per misurare la perdita di carico in una vite di acciaio ISO M6 avvitata nei getti di prova con un carico iniziale di 6 kN. I test sono stati effettuati in bagno di olio per tempi fino a 160 ore e a temperature costanti comprese tra 80 e 120°C. I test sono stati ripetuti due volte. Per l'analisi quantitativa del rilassamento delle leghe precaricate nelle differenti condizioni di prova è stata impiegata una equazione parametrica del tipo $\ln L = \alpha [Q/RT - \ln B - \ln t]$ dove L è il carico misurato al tempo t, Q è l'energia di attivazione del rilassamento, R è la costante universale dei gas, α e B sono costanti. I risultati mostrano che: 1) il decremento del carico iniziale che subisce prima una brusca riduzione e poi una diminuzione graduale senza mai raggiungere uno stato stazionario, 2) il decremento aumenta con la temperatura 3) in quasi tutte le curve del carico in funzione del tempo si ha un decadimento logaritmico, 4) alle temperature considerate, la lega No2 mostra la miglior resistenza al rilassamento, seguita dalla No5 e dalla No3. Mentre in quest'ultima il comportamento viene attribuito alla bassa resistenza al rilassamento delle dendriti prive di rame, nelle leghe No5 ed No2 il maggior contenuto di rame presente nei precipitati secondari aumenta sensibilmente la loro resistenza al rilassamento.

INTRODUCTION

Load relaxation is the time and temperature dependent decrease of load in a material due to conversion of elastic into inelastic (plastic) strain [1]. During this process, the total strain is kept constant, while the initial applied load decreases with time [2]. It has been shown that load relaxation is a problem in rivet and screw joints, particularly in automotive components where the temperature is usually high. It is also considered important in other stressed components, such as wheel rims and consoles for spring brackets in cars that are used in a warm climate [3].

Zinc alloy castings are widely used for automotive components due to their excellent mechanical properties, near-net shape capability and overall low manufacturing costs. In all these components, fasteners are used to fix them to other components and structures, or join individual parts together. The fasteners (bolts or screws) with normal or self-tapping thread forms are set in pre-threaded or plain holes [4].

Tightening the fasteners to a predetermined torque produces a tensile preload in the fastener. A small elastic displacement of the clamped parts does not increase the preload of the fastener appreciably because the fasteners are much less stiff than the bosses or flanges that they clamp together. Therefore, torques may be applied to fasteners safely and the initial normal stress is close to the yield stress for the material [5]. It is therefore possible to induce a high preload in the fastener such that the components are joined so tightly together that their relative movement is stopped and

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the whole structure is integrated for the projected life of the assembly. A study of the stress distributions in steel fasteners set into steel nuts has revealed [6] that most of the loading is concentrated on the first few threads of engagement, and also the distribution of the stress depends critically on the exact dimensions of the threaded parts.

Torque-relaxation has been observed in assemblies subjected to high service temperatures and creep effects may become significant. In automotive applications, the initial preload is lost progressively because vibration may cause gradual rotation of fasteners in their threaded holes. Both effects are detected by an apparent slackening (loss of torque) of the bolt or screw, which may be temporarily rectified by re-tightening. In steel assemblies, this problem has been found to be due to creep elongation of the fastener causing partial loss of the essential preload [7]. Due to the high melting temperature of steel, the creep process in steel fasteners is insignificant at temperatures less than about 350°C. On the other hand, creep may occur at near-ambient temperatures for zinc-rich alloys [8]. Thus for steel fasteners used in zinc alloy castings at a service temperature of more than $0.4T_m$, where T_m is the melting temperature of zinc alloys, the contribution of fastener creep is negligible, and any preload relaxation can be attributed to plastic deformation in the casting. During this process, creep allows a gradual displacement of the fastener relative to the casting, so that the preload is reduced.

EXPERIMENTAL WORK

CHEMICAL ANALYSIS OF ALLOYS

The chemical composition of the alloys was determined by atomic-absorption spectroscopy and the results are given in table 1.

The test specimens: The test specimens used for load relaxation tests were made from the sand castings of zinc alloys No3, No5 and No2. Alloys No3 and No5 were provided by Britannia Alloys and Chemical Ltd UK in the form of ingots with guaranteed composition while alloy No2 was prepared at the foundry of the University.

These high-zinc alloys No3, No5 and No2 represent a series in which the copper content increases from 0 to 0.85 to 2.8%, respectively whereas aluminium content is constant for all three alloys. The specimens were of cylindrical shape, having the following dimensions: length, 30 mm; diameter, 13 mm and bore (threaded), 6 mm. These specimens for all tests were produced on a lathe in the Manufacturing and Production Engineering Laboratory of the University. During the production of the test-pieces, the machining operation was carefully controlled so as to reduce the surface finish variations to a minimum.

TESTING EQUIPMENT

The equipment used for testing consists of a load-measuring device, an oil bath and a data-acquisition system. The load-measuring device was used for the continuous monitoring of load in the commercial fasteners used. It consisted of a short tension rod to which the head of the fastener was attached, which reacted the tensile stress in the fastener through a compression load cell. When the casting was screwed onto the fastener, it simulated the effect of inserting a screw into a hole. The load cell was used to measure the force exerted on the screw thread of a casting. It was a

Although no theoretical studies of this type of creep process are known, recently some preliminary experimental investigations [4, 5] showed that for steel screws in a range of commercial zinc alloy pressure-die castings, preload relaxation occurred rapidly at temperatures below 100°C. Since these preliminary tests were undertaken on zinc alloy pressure-die castings at temperatures up to 80°C, there was therefore a need to investigate the load relaxation process in these zinc alloys at higher temperatures with different casting process i.e. sand casting. Another objective of this study was to compare the load relaxation behaviour of the commercial zinc alloys under similar testing conditions.

The load-relaxation data has little further use unless some mathematical relationships are used to correlate it satisfactorily and allowing a quantitative analysis of the relaxation behaviour of alloys under different testing conditions. For this purpose, the relationship derived by Murphy [9] has been used to analyse the load-relaxation data of these alloys.

TABLE 1. CHEMICAL COMPOSITION OF THE EXPERIMENTAL ALLOYS.

	Al	Cu	Mg	Zn
No3	4.23	0.008	0.05	balance
No5	3.96	0.84	0.04	balance
No2	4.21	2.79	0.03	balance

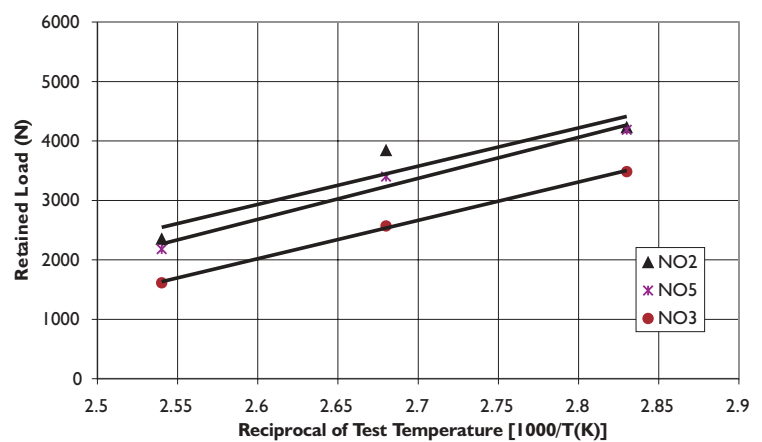
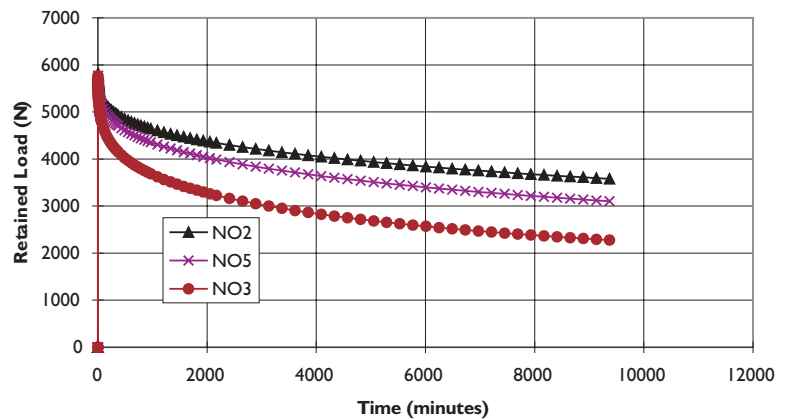
small, high capacity load cell, having a range of 0.15-13600 kg and its operating temperature range was -54 to 121°C. The oil-bath was used to heat the specimen and maintain the same temperature throughout the test. The maximum operating temperature of bath was 150°C, and had a temperature controlling accuracy of $\pm 0.1^\circ\text{C}$. At one time, up to seven specimens could be placed in the oil bath.

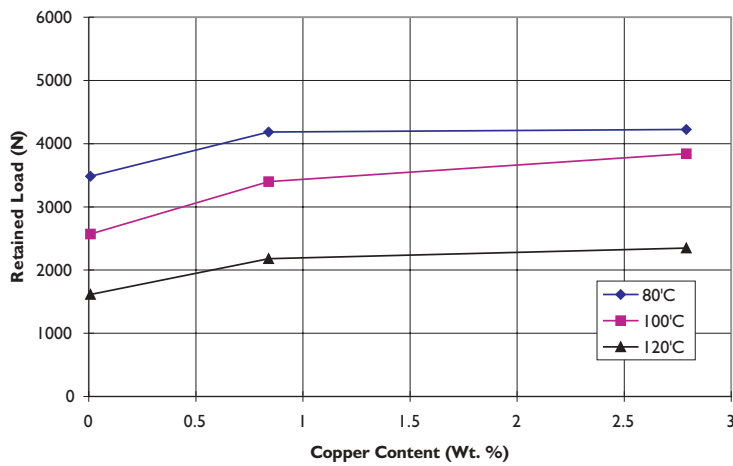
The data-acquisition system was used to record the results of tests in the form of retained load (N) versus the test time (Minutes). Variable speed logging was a useful feature provided by the system. This allowed to program the data logging speed to suit the application, i.e. at the initial stage of the tests, more data readings were measured and recorded than the later stages of the test. The time interval between two readings at the start of the tests was 5 and 10 seconds, whereas in the last stage of the tests, this interval was kept as one hour.

A M6x1 (ISO standard) threaded screw was locked into the tension rod, and the load monitor assembled. The test piece was then threaded onto the screw up to 16mm depth, which was the desired engagement of screw. The entire monitoring assembly was dipped into the hot oil at constant required test temperature, and left for about 2-3 hours to equilibrate. To start the experiment, the tension rod and screw were loaded by turning the fine-pitch nut at the top of the rod. This process was continued until the initial load of approximately 6000 N which was recorded

by the load cell, could be achieved. This whole process completed in a very short time, i.e. 15 ~ 20 s. The data-acquisition (logging) system was started as tightening commenced. The preload loss was then continuously monitored by the load cell for a period of up to about 155 hours, after which the test was terminated. Up to four tests were carried out simultaneously, and the test temperature was kept constant with a variation of $\pm 0.5^\circ\text{C}$. The results of experiments were recorded by data-acquisition system, and displayed on a computer in the form of time (Mins.) versus load (N) relaxed. All load relaxation tests were carried out in duplicate, and if results were not satisfactory, i.e. appreciable scatter was found in the results, some additional tests were also performed at those particular test conditions. The average values of the results were calculated and the mean values taken to represent the load relaxation behaviour of these zinc-based alloys.

The retained load (N) was measured continuously and plotted as a function of test time (Mins.) for all three alloys at 80, 100 and 120°C, the results are shown in fig. 1 at 100°C. In all cases, the initial load loss was high, decreasing gradually with time but not ceasing. The amount of load loss increased rapidly with test temperature and almost all of the curves approximated to a logarithmic decay of load with time although there was some variation in the initial part of the relaxation curves. This variation was probably due to the effect of localised shear creep of the threads in the castings, which caused a redistribution of the loading. The results indicated clear differences in the comparative resistance to load loss of these alloys. It was revealed that alloy No2 had the best resistance to load loss, with alloy No5 next and No3 worst at all temperatures as shown in fig. 1. Graphs were drawn to show the variation of retained load (N) with reciprocal temperature at 50, 100 and 150 h for all alloys, an example is shown for 100h, fig. 2. From these plots, the effect of short and long-term load relaxation tests can be observed. The graphs at 50 h time showed the short-term effects of load relaxation while 150h time graphs demonstrated the long-term effect. These plots showed that alloy No 2 was the best resistant to relaxation while No 5 was better than No 3 at both short and long time periods. To show the effect of copper content on load relaxation behaviour of alloys, the variation of the retained load (N) against the copper content (%) at different





Load relaxation data for the sand-cast zinc alloys during the current investigation was obtained from a limited number of tests of relatively short duration. This data has little further use unless some mathematical relationships are used to correlate it satisfactorily and allowing a quantitative

temperatures was plotted at 50, 100 and 150 hours, as shown in fig. 3 for 100 h. Alloy No3 was much inferior in load relaxation strength than alloys No5 and No2 at all temperatures, on the other hand alloy No2 was better than No5, but difference was greater at 100°C as compared to other temperatures. This indicated that for these alloys, the resistance to load relaxation increased with increasing copper content.

analysis of the relaxation behaviour of alloys under different testing conditions. For this purpose, the following relationship derived by Murphy [9] has been used to analyse the load-relaxation data:

$$\ln L = \alpha[Q/RT - \ln B - \ln t] \quad (1)$$

where L is the load after time t, Q is an activation energy for load relaxation, R is the universal gas constant, and α and B are constants. Using the experimental data, the mean values of constants α , $\ln B$ and Q were derived and finally the retained loads (N) were calculated for alloys by using the general equation for load relaxation (Eqn. 1) at 50°C, 80°C, 100°C and 120°C after 30,000 h of service time, as shown in table 2. The calculated values of retained loads (N) showed that alloy No2 was the best resistant to relaxation, then No5 and No3 was the worst at all temperatures.

Alloy	50°C	80°C	100°C	120°C
No3	1915	974	659	464
No5	2842	1595	1144	848
No2	3214	1934	1442	1108

Load relaxation is a phenomenon that is closely related to creep process and follows the same mechanisms as creep. It is therefore logical to analyse the results of load relaxation in the light of general creep theories. It has already been observed [10] that the rate-controlling mechanism operating in compressive creep of zinc alloys No3, No5 and No2 was dislocation climb. The current load relaxation results may therefore be analysed considering the dislocation climb as a rate-controlling process. From the analysis of load relaxation results and structure of the experimental alloys, it may be concluded that the higher copper content in alloys No5

and No2 contribute greatly to their relaxation strength in the form of second-phase (ϵ) particles [10]. These second-phase particles play an important role in preventing dislocation movement and therefore reducing the relaxation rate as observed for creep experiments of these alloys. The lower resistance to load relaxation of alloy No3 was mainly due to the lower relaxation strength of copper-free primary h dendrites, having greater volume than the eutectic in the microstructure. Copper also influences the

precipitation properties of alloys by increasing the precipitate volume and thus gives a certain strengthening. Alloys No5 and No2 showed much better relaxation strength than alloy No3, based

on precipitation hardening due to the presence of small copper-rich e-phase particles. Another well-known effect of copper additions to these alloys is a reduced tendency to inter-crystalline weakness due to copper-stimulated precipitation within the grains.

CONCLUSIONS

1. The preload relaxation equation: $\ln L = \alpha [Q/RT - \ln B - \ln t]$ could be used to correlate the experimental data of the zinc rich alloys
2. The retained loads determined from the experimental data showed that alloy No2 was the most resistant to relaxation, then No5 and No3 was the worst at all temperatures
3. The resistance to load loss increased with increasing copper contents under all testing conditions
4. The lower resistance to preload relaxation of alloy No3 was mainly due to the lower relaxation strength of copper-free primary η dendrites whereas in alloys No5 and No2, the higher copper contents contribute greatly to their relaxation strength in the form of second-phase (ϵ) particles
5. Dislocation climb was considered as the rate-controlling mechanism for load relaxation in these zinc alloys
6. The values of power law constants ie α and B generally increased with the increase of temperature. The mean values of α showed a decrease with the increase of copper content
7. The values of the activation energy Q were 95, 103 and 110 kJ/mole for alloys No3, No5 and No2, respectively, indicating an increase with the increase of copper content

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